Turbulent simulation of the flow around two cylinders in tandem configuration

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Abstract The turbulent flow around a generic configuration of a landing gear (the tandem cylinders) is simulated and analysed physically at $Re = 1.66\ 10^5$, by means of hybrid RANS-LES turbulence modelling approaches. In the present study, the Delayed Detached Eddy Simulation (DDES) approach has been employed for two cylinders spaced of $3.7D$ and with a height of $4D$. The DDES-OES modelling has been considered, especially involving turbulence length scale reconsiderations in the statistical part, by means of the Organised Eddy Simulation, (OES), to take into account non-equilibrium turbulence effects. The results are compared with experiments carried out at the NASA Langley Research Centre in the context of ATAAC EU-program in which the tandem cylinders is one of the stepping stones. In the present study, the benefits of these hybrid approaches have been discussed for capturing the vortex dynamics and frequency modes responsible for aerodynamic noise production in the context of landing gear configurations.

1 Introduction

Within the ATAAC (Advanced Turbulence Simulations for Aerodynamic Application Challenges) EU program, it has been shown through its main test–cases, that DDES (Delayed Detached Eddy Simulation) is a promising approach to capture the unsteady dynamics and the turbulence statistical content in strongly detached unsteady flows, by using reasonably fine grids, comparing to the grid sizes that would be needed by LES, for the present high-Reynolds number range flows around bod-

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ies, involving strong detachment. The present configuration highly interests aeroacoustics and aerodynamic noise control, generated by the two supports (tandem cylinders) of a generic configuration of a landing gear. The present test case has been the object of detailed experimental and numerical studies leaded by the NASA Langley Research Center, (Jenkins et al [5], Lockard [7, 8], among other). The experiments were carried out by standard 2D PIV, at Reynolds number 166 000. In order to avoid natural transition development, the experiments applied two transition strips at two specific upstream locations. A first synthesis of numerical simulations carried out for this test case was carried out by Lockhard, regrouping an order of 13 contributions involving different modelling approaches, as well as previous simulations by Khorrami et al. [6] using URANS-SST. These simulations indicated that the majority of the approaches captured quite well the Strouhal number of the vortex shedding frequency around the first cylinder, ($St = 0.24$) . Furthermore, as is seen in the ATAAC European program, the DES approaches better capture the complex vortex dynamics of the present flow, especially the formation of Kelvin-Helmholz vortices in the separated shear layers. In the experimental context, it was found that the shear layers formed downstream of the first cylinder wrap around the second cylinder and interact non-linearly with the complex turbulence background, producing predominant frequencies in the energy spectrum, in the range of acoustic noise.

The aim of the present paper is to evaluate the ability of the DDES methodology for an accurate prediction of the pressure fluctuations and frequencies responsible for the acoustic noise. In the present study, the DDES approach is considered, involving OES modelling (Braza et al. [3]), in the URANS part, accounting for improvement of the nearregion flow physics in respect of non-equilibrium turbulence. In Bourguet et al. [2], the DES-OES modelling was successfully applied for the simulation of the strongly detached flow around an airfoil beyond stall. The present DDES-OES, as the previous one, aims at providing a smooth passage from the URANS towards the LES region of flow detachment and at keeping the statistical region extent quite significant around the body.

2 Description of the test case

The test case is composed of two cylinders in in–line tandem configuration (see figure 1). The diameter (D) is identical for the both cylinders and the distance between the cylindres (center to center) is equal to $L = 3.7D$. The Reynolds number ($Re = U\ D/\nu$) associated with the diameter D is $Re = 166000$. The height of the cylinders is $H = 4D$. The Mach number is $Ma = 0.128$, corresponding to an incompressible flow. The Reynolds number is subcritical but it is closed to the drag crisis.

The experiments with the same parameters were conducted at the NASA Langley Basic Aerodynamic Research Tunnel (BART), which is a subsonic, atmospheric wind tunnel. The free stream velocity was set to 44m/s. The velocitie correspond to a Reynolds number based on the cylinder diameter of $Re = 166000$ and the distance between the cylinders is $L = 3.7D$. The difference with the present numerical study is the height of cylinder equal in the experiments to $H = 16D$. The free stream turbulence level at these conditions is about 0.09%. Figure 1 shows schematically the configuration with the tandem cylinders placed in the wind tunnel, as well as a sketch of the computational used.

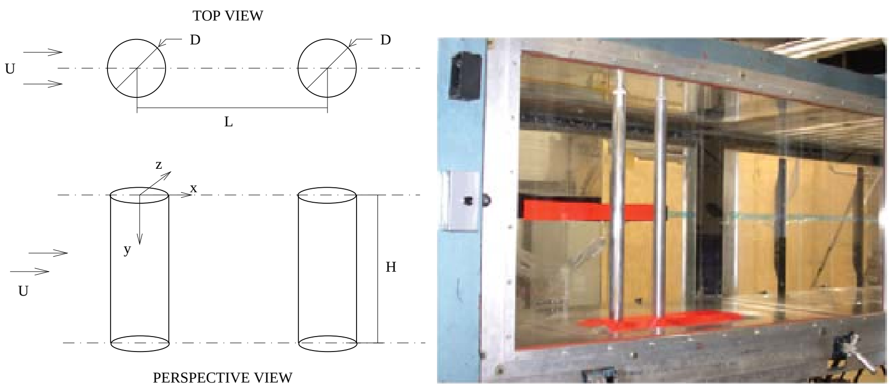

Fig. 1 Schematic representation of the two cylinders in in-line tandem arrangement (left) and picture of NASA experiment (right) for the dimensionless parameters $L = 3.7D$, $Re = 166000$

3 Numerical method and turbulence modeling

The simulations have been performed with the NSMB solver, (Navier-Stokes Multi Block), based on structured grids architecture. IMFT is part of the NSMB consortium (Vos et al. [9]), contributing with turbulence modelling development for strongly detached unsteady aerodynamic flows. For the present simulations, central difference scheme has been applied, among the variety of spacial discretisation schemes available in the solver, after performing detailed tests (Barbut [1], Gual et al. [4]). Dual time stepping is used for the temporal discretisation. The computational grid is of 16 millions of finite volumes. The closest point to the wall at the second cylinder is at a distance of $y/D = 3.0\ 10^{-5}$. The computations, using 512 processors in the present study, have been carried out at the SGI Altix supercomputer JADE of CINES, (Centre Interuniversitaire National de lEnseignement Suprieur) and at the supercomputer CURIE of the CEA (Commisariat dEtudes Atomiques) of France.

The time step is equal to $\Delta t = 0.001$ in order to be able to allow resolution of frequencies corresponding to a Strouhal number of order $St = 0.25$ and of higher frequencies predominant peaks due to Kelvin-Helmholtz eddies, responsible for the acoustic noise.

The turbulence modelling is the DDES approach, in which the RANS turbulence length scale is improved by means of the Organised Eddy Simulation (Braza et al. [3]). It is recalled that distinction of coherent and chaotic turbulent structures is performed in OES by dual spectrum splitting, solving the ensemble-averaged Navier-Stokes equations, where the turbulence stresses are modelled by modified turbulence scales modelling (as presented schematically in the figure 2). The fact that part of the spectrum to be modeled in OES extend from the low to the high frequencies allows the use of statistical turbulence modeling with appropriate modification due the non-equilibrium. In the time-domain, the equations are the phase-averaged Navier-Stokes equations. Due to the nonlinear interaction between the coherent part and the incoherent one, there is a slope modification of the inertial part in the spectrum, in the vicinity of the peak. This yields to a reconsideration of the Eddy-diffusion coefficient for the class of the two-equation modeling, as well as improved damping functions to attenuate turbulence towards the wall.

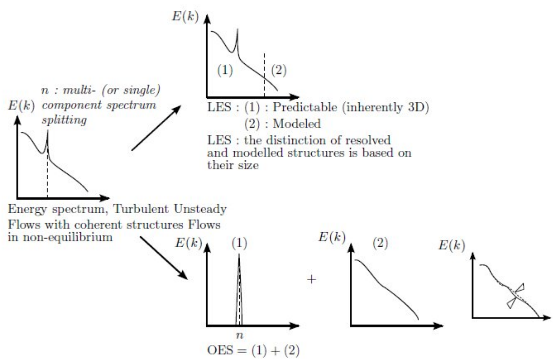

Fig. 2 Dual spectrum splitting : the distinction between the structures to be resolved and those to be modeled is based upon their organised or random character. Part (2) of the non-equilibrium energy spectrum has to be modeled by reconsidering advanced statistical turbulence modeling efficient in high-Re wall flows, due to the inertial-range modulation from equilibrium turbulence, schematically shown on the right.

4 Results

Figure 3 represents the instantaneous spanwise vorticity in the *y*-plane at the midle of the cylinder. The results obtained show a rich turbulence statistical content, as well as formation of alternating shear layers and the wrap around mechanism towards the second cylinder. The simulation shows a behavior qualitatively similar to that expected. The averaged streamlines field is shown in figure 3 (right) in comparison with the experiment. A good agreement with the experiments is achieved. It can be seen that the DDES–OES modelling provides fine shear layers, governed by the shedding of Kelvin–Helmholtz vortices, responsible for the acoustic noise.

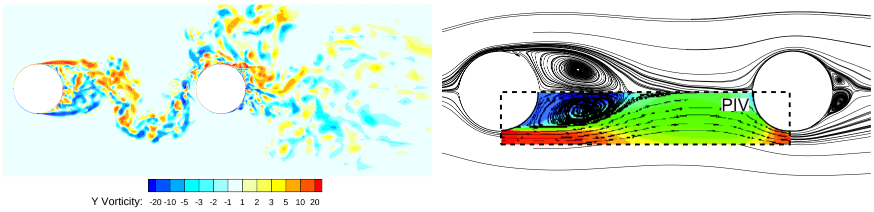

Fig. 3 Instantaneous spanwise vorticity contours (left) and averaged streamlines field for present study and NASA experiments (right)

Figure 4 shows the averaged pressure coefficient corresponding, where the pressure peaks values are quite closer to the experimental ones. Concerning the first cylinder, the averaged maximum pressure values are lower than in the experiment, where a better agreement is obtained for the second cylinder. In the numerical results, the detachment provides earlier than experiments and can explain the lower value of pressure.

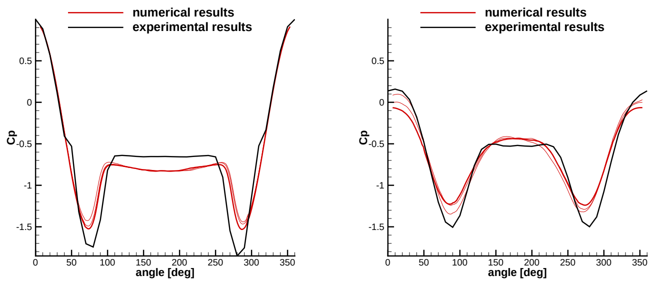

Fig. 4 Wall pressure coefficient (C_p) on the first cylinder (left) and the second one (right) copared with the experiment.

The 2D turbulence kinetic energy ($2DTKE = \frac{1}{2}(< u' >< u' > + < v'v' >)/U_\infty^2$) is performed and plotted along the x–line (in the gap region and rear the cylinders) and along the z–line (cross-flow) (figure 4). On the same x–line, the time averaged x-velocity is plotted (figure 4). The results are in good agreement and especially on the time averaged x-velocity. The 2D turbulence kinetic energy shows the same behaviour but it quite over–estimated in the gap region and it is quite underestimated in the rear of cylinder.

The power spectral density are performed with the time-evolution of the pressure at four points (two points in the upstream cylinder at 135°and two points in the downstream cylinder at 45°) and represented at the figure 6. The turbulence spectra show the principal instability modes, among which the Von Krmn mode, as well

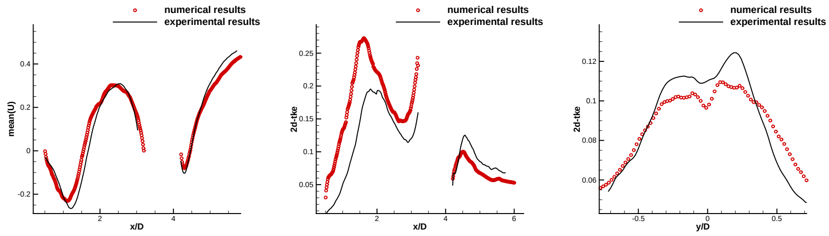

Fig. 5 Time-averaged velocity profile in the gap region and at the rear flow (left), the 2D turbulence kinetic energy following the same line (middle) and following the cross-line $x = 4.45$ (right)

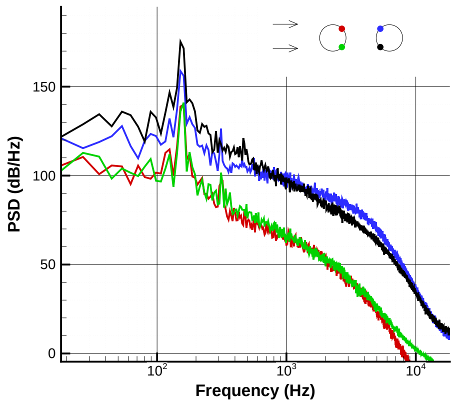

Fig. 6 Wall pressure spectra at four wall points on the first and second cylinder.

as formation of a spectral bump corresponding to the Kelvin-Helmholtz eddies. Of course, the chaotic turbulence effect provides the fact that these eddies are governed by a random vortex smearing around a predominant K-H mode. The main frequency is identical for the four points and the value is $159Hz$ ($178Hz$ for experiment). This frequency corresponds to the Von-Kármán vortex shedding. The seond pic corresponds to the second instability of Kelvin-Helmotz with a frequency of $316Hz$ always see by the four points (362 for experiment). A third pic is visible on the downstream cylinder ($476Hz$). We find similar frequencies to those obtained by experiment with a slight underestimation.

5 Conclusion

A numerical study has been carried out to analyse the complex vortex pattern around two cylinders in tandem at Reynolds number 166,000, by means of Hybrid Turbulence modelling approaches. The Delayed Detached Eddy Simulation DDES-SST has been applied and comparison of results with the experiment is carried out. The results have shown that the flow structure between the two cylinders and past the second cylinder are well produced by the present methods. The statistical content of the DDES-OES is detailed and the shear layer interfaces are fine and contain a number of Kelvin-Helmholtz vortices. Moreover, the spectral analysis shows that the flow is mainly governed by the von Krmn mode. A reasonably good agreement with the experiments carried out in the NASA-Langley Research Center is shown, especially concerning the mean streamlines structure, velocities and predominant frequencies. The interaction between the Von Krmn mode and the shear layer frequencies bump is quantified by means of advanced signal processing. The present study shows the ability of the DDES to simulate the present complex flow dynamics and predominant modes, associated with landing gear aerodynamic noise.

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